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Nonequilibrium Fermi Gases

John Thomas
North Carolina State University at Raleigh

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Final Report

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
During this period, we made important breakthroughs in the optical control of two-body interactions in ultra-cold gases. We have studied magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a 6Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

A major breakthrough in our understanding is the experimental verification of a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with all of our loss measurements for both broad and narrow resonances. Using this model, we show that our method substantially reduces the two-body loss rate compared to single field methods for same tuning range.

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Fermi gases, non-equilibrium, optically-controlled interactions

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Grant Title: “Nonequilibrium Fermi Gases.”
Grant # FA9550-13-1-0041
Period: 3/1/2013-2/29/2016
Contract Officer: Tatjana Curcic

Abstract (250 words)

We study the control magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a ^{6}Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

A major breakthrough in our understanding is the experimental verification of a new model of light-induced loss spectra, employing continuum-dressed basis states, which agrees in shape and magnitude with all of our loss measurements for both broad and narrow resonances. Using this model, we predict the trade-off between tunability and loss for the broad resonance in ^{6}Li, showing that our two-field method substantially reduces the two-body loss rate compared to single field methods for same tuning range. We show that the EIT method creates narrow features in the scattering phase shift, enabling control by optical frequency rather than intensity, providing a general method of suppressing unwanted changes in the total trapping potential.

Publications:

1) E. Elliott, J. A. Joseph, and J. E. Thomas, “Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases,” Phys. Rev. Lett. **112**, 040405 (2014).

2) E. Elliott, J. A. Joseph, and J. E. Thomas, “Anomalous Minimum in the Shear Viscosity of a Fermi Gas,” Phys. Rev. Lett. **113**, 020406 (2014).

3) J. A. Joseph, E. Elliott, and J. E. Thomas, ``Shear viscosity of a unitary Fermi gas near the superfluid phase transition," Phys. Rev. Lett. **115**, 020401 (2015), selected as an *Editor's Suggestion*.

4) A. Jagannathan, N. Arunkumar, J. A. Joseph, and J. E. Thomas, "Optical control of magnetic Feshbach resonances by closed-channel EIT," submitted to Phys. Rev. Lett.

Accomplishments:

1) Optical control of magnetic Feshbach resonances.

During the period of this grant, we have made several breakthroughs in both our theoretical approach and our experimental approach to developing general methods for tuning two-body interactions in ultracold gases, using the frequencies of the optical fields as control parameters. By avoiding intensity changes in the control beams, we implement a general method of avoiding unwanted tuning of the net trapping potential, which arises from both the external trap and the optical beams. Our experiments include the following accomplishments:

- In the first experiments, we developed a diode-laser system for generating two optical fields to excite the strongest v = 38 to v' = 68 transition (control beam) and a much weaker v = 37 to v' = 68 molecular transition (EIT beam) in the closed molecular channel of the 1-2 Feshbach resonance in ^{6}Li. The molecular wavelength is 1.5 nm detuned from the atomic transition, suppressing direct optical scattering. The two fields differ in frequency by 57 GHz, with a frequency jitter < 100 kHz. This is achieved using a master diode laser, which is locked to a saturation resonance in iodine vapor. The master laser enables stabilization of an optical cavity to which two additional diode lasers are locked, generating the control and EIT fields needed to create a dark state in the closed molecular channel of a magnetic Feshbach resonance.
- We have demonstrated up to 3 G tuning of optically induced loss features in the narrow Feshbach resonance of ^{6}Li.
- We have increased the lifetime for the broad resonance from 0.5 ms with a single beam tuning method to 0.4 sec with our two-field EIT method. This is an important achievement, as the very large background scattering length in ^{6}Li, -1405 a_0, produces a very large two-body loss rate constant. A-priori, it was not obvious that this suppression could be achieved in real experiments, which are limited by relative frequency jitter.
- A major breakthrough was achieved recently in locking the diode lasers to the v = 38 to v' = 64 and v = 37 to v' = 64 transitions. As noted in Robin Cote's thesis, these transitions achieve a very good compromise in the strengths of the two coupled transitions. The v = 37 to v' = 64 transition is now so strong that we obtain the same Rabi frequency with 2 mW as we did for the v = 37 to v' = 68 transition with 100 mW, greatly increasing the EIT window.
- We have located and tuned the ^{6}Li p-wave Feshbach resonances. This is very important for studies of the effective range, which can be controlled by the two-field method at the point of minimum loss. The p-wave binding energies are large and strongly dependent on the effective range, making this system optimum for these studies. In addition, this system will enable studies of optically-controlled superfluidity in p-wave systems in reduced dimensions (pancake-shaped traps).

On the theoretical front, we have developed a new continuum-dressed state model of optically controlled magnetic Feshbach resonances. Import results include:

- We have solved a long-standing problem with the theory of optical control for broad Feshbach resonances. All previous treatments of optical control use adiabatic elimination of the excited molecular electronic state in the closed channel to obtain tractable results. Near resonance, this requires that the rate of change of the ground state amplitudes (Rabi frequencies) are smaller than the spontaneous emission rate γ_e. Unfortunately, this method is invalid in the bare basis for broad resonances, where the hyperfine coupling constant is much larger than the γ_e, causing rapid changes in the amplitudes of the bare basis states. Instead, we use the full Feshback resonance scattering states and dressed bound state as the basis. Since the hyperfine coupling is already included in this basis, the amplitudes of these states slowly vary, enabling adiabatic elimination of the excited state amplitude. As the basis is complete and includes correctly the optical couplings, it is valid for narrow resonances as well and reduces prior results valid only in the narrow resonance regime.
- We have validated our dressed-continuum state approach by comparing predictions to measured one- and two-field loss spectra. We find very good agreement in shape and absolute magnitude, using the measured Rabi frequencies.
- We are able to predict the relative momentum dependence of the two-body loss rate constant, enabling a new study of the trade-off between loss and tuning in optical control methods.
- Using the new model, we are able to show that the maximum loss rate the two-field optical control method is much smaller than that of single-field methods, for the same change in the zero energy scattering length. We find that the two-field methods enable symmetrical tuning of the scattering length about the minimum loss point, by changing the optical frequency of the control beam. In contrast, single-field methods achieve low loss only for large detunings, requiring much larger frequency changes than two-field methods for the same change in the scattering length.
- The new model shows that two-field method produces narrow features in the scattering phase shift, demonstrating that optical frequency changes can be used to tune the scattering length, rather than intensity. This provides a general method of avoiding unwanted changes in the effective atom trapping potential as the two-body parameters are tuned.
- Finally, the new model shows that the effective range can be controlled at the point of minimum loss, analogous to the EIT method of controlling dispersion in atomic vapors with suppressed absorption.

2) Thermodynamics of two-dimensional, spin-imbalanced Fermi gases.

3) Scale-invariance and viscosity measurements in strongly interacting Fermi gases.

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The full title of the funded effort.

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FA9550-13-1-0041

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John E. Thomas

Program Manager
The AFOSR Program Manager currently assigned to the award

Tatjana Curcic

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Abstract

We study the control magnetic Feshbach resonances in an optically-trapped mixture of the two lowest hyperfine states of a 6Li Fermi gas, using two optical fields to create a dark state in the closed molecular channel. In the experiments, the narrow Feshbach resonance is tuned by up to 3 G. For the broad resonance, the spontaneous lifetime is increased from 0.5 ms for single field tuning to 0.4 s at the dark state resonance, despite the large background scattering length.

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Archival Publications (published) during reporting period:

1)E. Elliott, J. A. Joseph, and J. E. Thomas, "Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases," Phys. Rev. Lett. 112, 040405 (2014).

2)E. Elliott, J. A. Joseph, and J. E. Thomas, "Anomalous Minimum in the Shear Viscosity of a Fermi Gas," Phys. Rev. Lett. 113, 020406 (2014).

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Research Objectives

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